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ISENTROPIC COMPRESSION OF METALS, AT MULTI-MEGABAR PRESSURES, USING HIGH EXPLOSIVE PULSED POWER*

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Abstract

Accurate, ultra-high pressure isentropic equation of state (EOS) data, are required for a variety of applications and materials. Asay [1] reported a new method to obtain these data using pulsed magnetic loading on the Sandia Z-machine. Fast rising current pulses (risetimes from 100 to 300 ns) at current densities exceeding many MA/cm, create continuous magnetic loading up to a few Mbar. As part of a collaborative effort between the Los Alamos and Lawrence Livermore National Laboratories we are adapting our high explosive pulsed power (HEPP) methods to obtain isentropic EOS data with the Asay technique. This year we plan to obtain isentropic EOS data for copper and tantalum at pressures up to ~2 Mbar; eventually we hope to reach several tens of Mbar. We will describe the design of the HEPP systems and show our attempts to obtain EOS data to date.

I. HEPP - ICE CONCEPT

A. Introduction

The isentropic compression experiment (ICE) is a relatively new technique that has been demonstrated by Asay et al. on the Sandia Z-Accelerator. Smoothly rising (shock-free) mechanical compression waves have been propagated into various samples by electromagnetic loading at pressures in excess of 1 Mbar. High quality isentropic (shock-free) EOS data have now been obtained for many materials including copper and tantalum [2]. ICE experiments have also been performed on insulating materials, including high explosives [3].

One significant advantage of the ICE experiment, compared to gas-gun experiments, is that the EOS data are acquired continuously, from zero up to the peak pressure in one experiment, i.e., a complete EOS curve is obtained in one shot.

The Sandia Z-Accelerator is a 4-MV machine modified to deliver currents of 20 MA in risetimes of 100 ns to 300 ns to a variety of loads. In this paper we will describe a compact, high explosive pulsed power (HEPP) system, designed to perform the same ICE experiments,

and to eventually extend the scope of the work to higher pressures.

While the application of HEPP to ICE is novel, all of the components in the HEPP-ICE system existed prior to ICE and have been adapted from other applications. However, the ICE experiment does require a timing precision of 20 to 40 ns, which is much less than is normally expected from an HEPP system.

This program is some nine months old (at the time of this conference), and there has not been time to produce a useful isentropic compression data shot. We will describe the pulsed power aspects of this work, and report our progress to date in designing, developing and testing this system for ICE studies.

II. PRINCIPLES OF ICE

The physics of ICE, and the methods of data recovery and analysis are described by Reisman [2]. The basic principle of ICE is the magnetic loading of a sample situated adjacent to a pair of parallel conductors, Figure 1. If equal opposing currents per unit width flow in the conductors, J , then the magnetic pressure applied to the inside

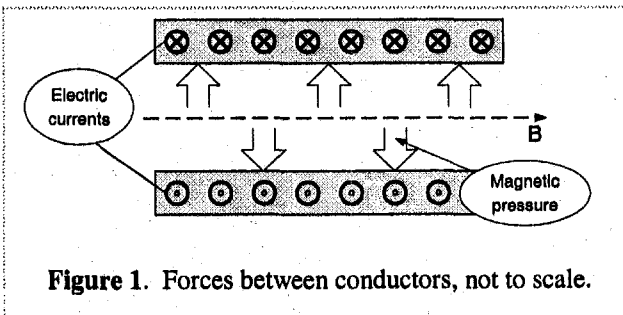


Figure 1. Forces between conductors, not to scale.

surfaces is $P_B = \frac{1}{2}\mu_0 J^2$ in SI units. If $J = 10^8$ A/m, then the magnetic pressure $P_B = 2\pi$ GPa (62.8 kbar). Similarly, for $J = 2 \times 10^9$ A/m, $P_B = 2.51$ TPa (25.1 Mbar).

If the time of application of these currents is short, compared to the time it takes a compression wave to traverse the conductor and back again, then the high pressures can be reached before the conductors have time to move apart. In the ICE experiments the currents are rapidly

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switched into the conductor, typically with risetimes of 300 ns ($dI/dt \sim 3 \times 10^{13}$ A/s).

A. Risetime of currents.

By definition, isentropic experiments must be shock-free. One key feature of ICE is the shape of the current profile. Asay has shown that current profile tailoring delays the transition of the ramp wave to a shock, i.e., abrupt changes in dI/dt , especially at the beginning of current flow, lead to the early development of shocks in the sample. Consequently, the Z-machine has been modified to slow down and shape the current rise over a 300 ns period (from the original 100 ns). We will show that current shaping is easily achieved with HEPP-ICE. Our calculations show that such shaping should allow us to reach 2.5 TPa (25 Mbar) in 3 mm thick samples.

B. HEPP approach.

Ongoing HEPP-ICE studies are concentrating on a compact explosive flux compression generator (FCG) system capable of delivering 10 MA ($dI/dt \sim 3 \times 10^{13}$ A/s) into loads of 1 to 2 cm width with the required risetimes. This produces isentropic compression at pressures in the range of 100 to 500 GPa (1 - 5 Mbar). The FCG is a plate generator described by Erickson [4]. This is a simple, inexpensive FCG that in these experiments amplifies a 1.9-MA seed current to 12 MA into a storage inductor of ~ 50 nH. There are several geometries of these FCGs, including the 102x127-mm (designed for high output dI/dt applications), and the 4-inx5-in, see Goforth [5]. The FCG current risetime is too slow for ICE (2×10^{12} A/s), so high voltage signal conditioning is provided by an explosively formed fuse (EFF) opening switch [4],[6]. The total output inductance of the EFF system and its load is typically 6 nH, which means that to achieve $dI/dt = 3 \times 10^{13}$ A/s a voltage of 180 kV is required [7].

1) System

The HEPP-ICE system comprises six basic components shown in Figure 2: a 12 mF, 20 kV capacitor bank; the plate FCG; a storage inductor; the EFF; a pulse shaping system of closing switches; and the load [8].

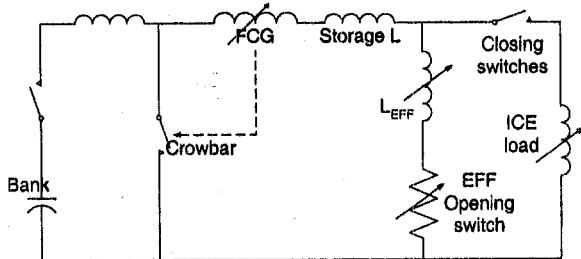


Figure 2. Basic HEPP-ICE circuit.

2) EFF design.

With the exception of the staged closing switches, the HEPP system comprises off-the-shelf components that have been adapted to this application. For HEPP-ICE,

the EFF switch must produce a peak resistance of 85 m Ω . In the first three preparatory experiments (ICE 1- 3) we attempted to use a simple, planar EFF configuration [5]. However, this simple switch was not capable of withstanding the high voltages, and we changed to a cylindrical EFF design of the next experiment, ICE-4, described in section IV.

3) Staged closing switches

To provide isentropic loading, the optimum current rise for ICE starts with a relatively small dI/dt and smoothly increases to the peak. In HEPP-ICE, simply combining two or more switches in parallel, each with its own series inductor, does this. The largest inductance (L_{hi}) is switched on first, thus providing a small dI/dt , followed by the smaller inductance for a higher dI/dt , as in Figure 3. The relative inductances and delays between clo-

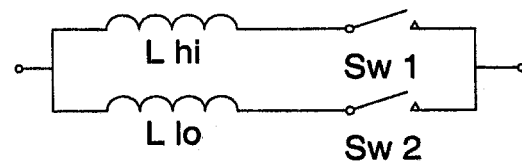


Figure 3. Staged closing switches.

sures control the current shape. Typically the first inductance might be 8 nH, and the second 0.5 nH with a delay between closures of 300 or 400 ns. The resultant waveform is seen in Figure 4. Note the change of slope at 400 ns when Sw2 is closed. This technique can be extended with more parallel switches to tailor a wide range of current profiles.

4) Closing switches and jitter control.

Timing of the closing switches is critical for achieving the correct current profile. From the cumulative data of 20 tests we found that the "Procyon-style" closing switches [9] had a standard deviation (σ) from the mean delay of 39 ns at 13 kV. However, σ increased with applied voltage across the switch, reaching 96 ns at 140 kV, the voltage at which the first switches were required to close in HEPP-ICE. This σ was too large for ICE. If the switches closed too late, then the rapidly rising EFF could

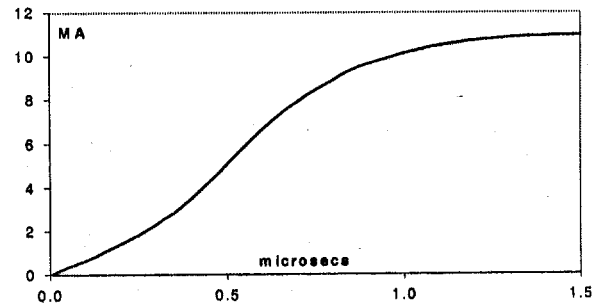


Figure 4. HEPP-ICE switched current profile.

exceed the breakdown strength of the circuit insulation voltage ($dV_{eff}/dt = 4 \times 10^{11}$ V/s and $dV/dt \times \sigma \approx 40$ kV). To correct this we chose to connect four of the switches in

parallel (so that Sw1 and Sw2 each comprised four switches). This reduced the probability of late switch closure from 50% to 5% (for the mean delay) – and had the added advantage of reducing the overall switch inductance by four.

5) EFF timing

The EFF is precisely timed by a coaxial detonation system developed at Los Alamos. We performed a camera test to determine the exact timing of the EFF. Piezo-pin and Imacon streak camera diagnostics measured the delay and showed a uniform surface ripple of 40 ns over the entire length of the switch.

III. CIRCUIT MODELING OF HEPP-ICE

For experimental design and subsequent data analysis it is important to have good predictive models of the system performance. For the basic HEPP-ICE circuit this is not straightforward. The capacitor bank and closing switches may be modeled by simple circuit parameters. But the other circuit components are dynamic. The inductances of the plate FCG, EFF, and load all change dynamically during the experiment, and of course, the EFF resistance is a dynamic function of time. Accurate models had to be developed for each.

A. FCG Model

The plate generator was modeled using tables of inductance vs. time, $L(t)$, and rate of change of inductance versus time, $dL(t)/dt$ derived from published data [4]. These data had been obtained by numerical modeling of the generator inductance $L(t)$. Then the $dL(t)/dt$ data were obtained by fitting the model predictions to experimental results. Note that the $dL(t)/dt$ data include the actual resistive losses of the FCG, $R(t)$, (i.e., they could not be separated) and the integral of $dL(t)/dt$ does not equal $L(t)$.

B. Load Model

The load inductance increases with time as the magnetic loading on the conductors moves them apart, so we had to calculate both $L(t)$ and $dL(t)/dt$ as functions of time and current. This was an iterative process.

1) Current and inductance.

First we estimated the inductance and calculated the current for the circuit. From that calculated current we obtained the plate separation (described below) and thus $L(t)$ and $dL(t)/dt$. From these new inductance data we recalculated the current, and so on. Typically the calculations converged after three iterations.

2) Separation calculation.

To find the plate separation we calculated the magnetic pressure using $P_B = \frac{1}{2}\mu_0 J^2$, assuming uniform magnetic loading, then obtained the particle velocity of the plates from the known copper EOS. The inductance was then

calculated using an exact expression (allowing for edge effects) for a parallel plate transmission line.

C. EFF Model

The EFF model was a combination of a resistance versus time relationship, $R(t)$, and a calculated inductance model, $L(t)$ and $dL(t)/dt$. The $R(t)$ data were obtained from small scale experiments on annealed aluminum-1100 [5]. For the inductance we calculated the coaxial values for the initial and final ratio of radii, L_i and L_f , and the initial dL/dt obtained from the initial velocity of the EFF liner. Then we assumed an exponential form of inductance versus time, $L = (L_i - L_f)e^{-t/\tau} + L_f$, and solved for τ from $dL/dt = -(L_i - L_f)/\tau$ at $t = 0$.

D. Circuit Code

The FCG, load and EFF models were combined with the other circuit parameters in a circuit code or spreadsheet to predict performances of various ICE systems.

IV. EXPERIMENTS SO FAR

We have been able to fire just four experiments so far, ICE 1-3 with a simple planar EFF, and ICE-4 with the coaxial EFF. The first three were proof-of-principle shots were designed to demonstrate the pulsed power capability for ICE, and the last shot was our first attempt to produce EOS data.

A. ICE 1-3

These were fired in Sept/Oct 2000, and were designed to demonstrate the viability of HEPP-ICE with the simplest and cheapest EFF we had in stock. These were only pulsed-power experiments and did not include the diagnostics for EOS measurements. We found that this planar EFF could neither sustain the high voltages nor the high currents necessary for ICE, and the EFF was abandoned for the coaxial version mentioned before. The best waveform we obtained in ICE-3 had a peak current of 4 MA (in a 2-cm wide load) with a rise of 1 μ s. However, the current rise was smooth, thus proving that the staged closing switches could provide shock-free current profiles.

B. ICE-4

This was our first attempt to obtain EOS data with HEPP-ICE. The circuit comprised: a 102x127-mm plate FCG; a 40 nH storage inductor; a 180 kV EFF; two sets of parallel closing switches (with 8 nH and 0.5 nH) delayed by 300 ns; and a 2-cm wide load. The experiment was designed to deliver 10 MA to the load, with a waveform similar to Figure 4, and a peak pressure of 157 GPa. Unfortunately the shot failed, as described below.

1) EFF

A new EFF was built for this shot, designed for 180 kV and 10 MA operation. It uses an annealed 1100-

aluminum cylindrical conductor, 812 μm thick, 203.2-mm diameter and 223.5 mm long – instead of the conventional 6061-T6 aluminum used in previous EFF designs. The switch is driven by a 203.2-mm cylindrical PBX-9501 explosive charge, which is simultaneously detonated along its central axis. The switch die is a 225-mm diameter Teflon tube, with 29- 1.50 mm-wide anvils and 30- 6.00-mm spaces, making thirty “patterns” over a length of 223.5 mm; the cavity depths are 12.7 mm.

2) Load Design

A sketch of the load section used in ICE-4 is shown in Figure 5. The load section was a copper transmission

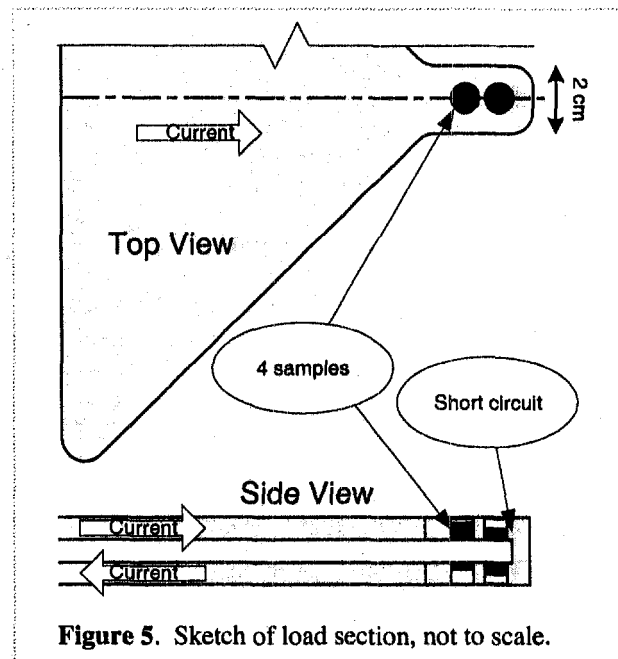


Figure 5. Sketch of load section, not to scale.

line (tapered to minimize inductance) converging from a width of 30 cm to 2 cm with an angle of 45° (the top edge of the sketch is cut to save space). The two conductors were separated by 0.5 mm and insulated with nine sheets of 50 μm (2 mil) thick Kapton, and the sample area was 4 cm long. Four copper samples, each 10 mm diameter, were mounted in the load section as shown with thicknesses of 1.75, 2.0, 2.25, and 2.5 mm. The back face of each sample was evacuated to a pressure of $\sim 10 \mu\text{m}$ to eliminate air flash and the particle velocity of each was measured by a multi-point VISAR system. The 2.0-mm thick sample had nine individual VISAR points, arranged in a cross across its surface, to determine the flatness of the pressure drive. The magnetic loading on the inside surfaces, as described previously, exerted pressure on the four samples.

3) Results

There were two fundamental problems, one with the FCG and the other with the EFF. The 102×127-mm FCG produced too high a dI/dt , i.e., we used the wrong FCG, which combined with the load inductance of a 50 nH load would have created a voltage of $\sim 200 \text{ kV}$, caus-

ing breakdown in the output insulation. Secondly, we had a failure of the EFF detonation system, which prevented it from generating the voltage required for the experiment.

Consequently, current transfer to the load was only $\sim 3 \text{ MA}$ and very slow ($dI/dt \sim 1 \text{ TA/s max}$) – as confirmed by Faraday diagnostic current data and VISAR signatures.

V. SUMMARY

We have reported our progress towards developing an HEPP-ICE system in the last nine months. Teething problems have prevented us from obtaining EOS data, yet we expect to produce EOS data for copper and tantalum in the next few months, at pressures from 0 to $\sim 1.5 \text{ Mbar}$.

Long term, we will work towards a 25-Mbar system based on the Ranchero flux compression generator (50 - 90 MA)[10], and operating at 500 kV.

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